

## ***CP* Violation and Flavor Changing Effects in *K* and *B* Mesons from Nonuniversal Soft Breaking Terms**

A. Masiero and O. Vives

*SISSA-ISAS, Via Beirut 4, I-34013, Trieste, Italy*

*and INFN, Sezione di Trieste, Trieste, Italy*

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We analyze *CP* violation and flavor changing effects in a minimal supersymmetric standard model with arbitrary nonuniversal soft breaking. Large flavor changing neutral current effects are naturally expected in the *K* system, even in the absence of quark-squark flavor misalignment. However, the *B* system is sensitive to new supersymmetric contributions only if nonuniversality implies, not only different soft terms for the three generations but also a large quark-squark misalignment. The only exceptions are processes with a leading chirality changing contribution proportional to  $\tan\beta$  (as  $b \rightarrow s\gamma$ ).

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*CP* violation and flavor changing neutral current (FCNC) experiments are a main arena where searches of new physics beyond the standard model (SM) of electroweak interactions will take place in the near future. In these processes, SM contributions are small and hence new contributions are allowed to compete on equal grounds. In fact, the currently available experimental information allows us to set stringent bounds on any extension of the SM in the neighborhood of the electroweak scale. The so-called minimal supersymmetric extension of the SM (MSSM) constitutes one of the most interesting examples of this. Indeed, it is well known that a general MSSM with completely arbitrary soft-breaking terms tends to overproduce FCNC and *CP* violation effects, and this is used to set stringent bounds on the structure of the sfermion mass matrices [1]. However, the size of FCNC and *CP* violation effects are strongly dependent on the supersymmetry soft breaking terms which finally define a particular MSSM. In a recent work [2,3], we showed that in the absence of new flavor structures no sizable supersymmetric (SUSY) contributions to *CP* violation observables, such as  $\varepsilon_K$ ,  $\varepsilon'/\varepsilon$ , or hadronic  $B^0$  *CP* asymmetries, can be expected. In contrast, the presence of nonuniversality in the trilinear terms, expected in string theories [4,5], is already enough to generate large supersymmetric contributions to  $\varepsilon'/\varepsilon$  [6–8]. Unfortunately, the large theoretical uncertainties in the SM prediction prevent us from using this observable to identify these new supersymmetric contributions.

In this Letter, we will address the problem of indirect SUSY discovery in the framework of a completely general MSSM (see our definition below). This analysis does not intend to exhaust every single possibility, but rather to provide a general view of the “natural” SUSY effects. To our knowledge, such a study is so far absent in the literature. The common attitude towards this problem consists of a pure phenomenological analysis through the mass insertion (MI) approximation [1,9]. However, we will show that the inclusion of very general and reasonable theoreti-

cal requirements has a deep impact on the expectations of these SUSY effects when compared with MI bounds. In particular, we will see that while large supersymmetric effects in hadronic *B* *CP* asymmetries are possible only under some special conditions [10], in the kaon system these are naturally expected in any model with nonuniversal soft-breaking terms. More precisely it follows: (i) If the new SUSY flavor structure is given by nonuniversal flavor diagonal soft terms, then only the kaon system is sizably affected in FCNC and *CP* violation processes [however, observables with a dominant chirality changing part proportional to  $\tan\beta$  ( $b \rightarrow s\gamma$ ,  $b \rightarrow sl^+l^-$ , ...) escape this rule, even in the absence of new flavor, for large  $\tan\beta$  [2,11]]. (ii) If SUSY signals are to be seen in *CP* violating hadronic *B* decays, then it implies the presence not only of flavor diagonal nonuniversality, but also a rather large quark-squark flavor misalignment [much larger than Cabibbo-Kobayashi-Maskawa (CKM) mixings].

In this context, it is interesting to comment on the new results for the  $B \rightarrow J/\psi K_S$  *CP* asymmetry recently obtained by BaBar and BELLE [12]. Taking into account the above statements, a generic MSSM is likely to produce a sizable effect in  $\varepsilon_K$ , possibly lowering this asymmetry. However, a direct contribution to the  $B^0$  *CP* asymmetry is possible only under special conditions and usually associated with a large contribution in the kaon system.

In the first place, we define our MSSM through a set of four general conditions: (i) *Minimal particle content*: We consider the MSSM, the minimal supersymmetrization of the standard model with no additional particles from  $M_W$  to  $M_{\text{GUT}}$ . (ii) *Arbitrary soft-breaking terms*  $\mathcal{O}(m_{3/2})$ : The supersymmetry soft-breaking terms, as given at the scale  $M_{\text{GUT}}$ , have a completely general flavor structure, however, all of them are of the order of a single scale,  $m_{3/2}$ . (iii) *Trilinear couplings originate from Yukawa couplings*: Although trilinear couplings are a completely new flavor structure they are related to the Yukawas in the usual way:  $Y_{ij}^A = A_{ij} \cdot Y_{ij}$ , with all  $A_{ij} \approx \mathcal{O}(m_{3/2})$ . (iv) *Gauge coupling unification at  $M_{\text{GUT}}$* .

In this framework, to define our MSSM, all we have to do is to write the full set of soft-breaking terms. This model includes, in the quark sector, seven different structures of flavor,  $M_{\tilde{Q}}^2$ ,  $M_{\tilde{U}}^2$ ,  $M_{\tilde{D}}^2$ ,  $Y_d$ ,  $Y_u$ ,  $Y_d^A$ , and  $Y_u^A$ . However, these seven matrices are not completely observable; only relative misalignments among them are physical. Hence, we have the freedom to choose a convenient basis. At the supersymmetry breaking scale,  $M_{\text{GUT}}$ , the natural basis, especially from the point of view of the SUSY breaking theory, is the basis where all the squark mass matrices,  $M_{\tilde{Q}}^2$ ,  $M_{\tilde{U}}^2$ ,  $M_{\tilde{D}}^2$ , are diagonal. In this basis, the Yukawa matrices are  $v_1 Y_d = K^{D_L \dagger} \cdot M_d \cdot K^{D_R}$  and  $v_2 Y_u = K^{D_L \dagger} \cdot K^\dagger \cdot M_u \cdot K^{U_R}$ , with  $M_d$  and  $M_u$  diagonal quark mass matrices,  $K$  the CKM mixing matrix, and  $K^{D_L}$ ,  $K^{U_R}$ ,  $K^{D_R}$  unknown, completely general,  $3 \times 3$  unitary matrices.

In a basis independent language the matrices  $K^{D_L}$ ,  $K^{D_R}$ ,  $K^{U_L}$ , and  $K^{U_R}$  measure the flavor misalignment among  $d_L$ - $\tilde{Q}_L$ ,  $d_R$ - $\tilde{d}_R$ ,  $u_L$ - $\tilde{Q}_L$ , and  $u_R$ - $\tilde{u}_R$ , respectively. All we know experimentally of these matrices is that there is, indeed, a minimum degree of misalignment among  $K^{D_L}$  and  $K^{U_L}$ , described by the CKM mixing matrix  $K^{U_L} \cdot K^{D_L \dagger} = K$ . This relation can be used to fix one of these matrices and there remain three unknown matrices,  $K^{D_L}$ ,  $K^{D_R}$ , and  $K^{U_R}$ . From the phenomenological point of view, we could have two complementary pictures. If the source of flavor structure in the SUSY breaking sector is completely independent from the source of flavor in the Yukawa sector, these matrices are completely arbitrary and large mixings are possible. However, if the flavor structure in the Yukawa sector and the soft-breaking terms have a common origin or are somehow related, they can be expected to be close to the identity or to the CKM mixing matrix. As we will see below, these two scenarios have very different phenomenological consequences. Finally, the trilinear matrices,  $Y_d^A$  and  $Y_u^A$ , are specified in this basis by the SUSY breaking theory as  $Y_{ij}^A = A_{ij} \cdot Y_{ij}$ .

Once we specify these 7 matrices, our MSSM model is fully defined at the  $M_{\text{GUT}}$  scale. However, experimentally measurable quantities involve the sfermion mass matrices at the electroweak scale. So, the next step is to use the MSSM renormalization group equations (RGE) [13,14] to evolve these matrices down to the electroweak scale. Below the electroweak scale, it is more convenient to work in the SCKM basis where the same unitary transformation is applied to both quarks and squarks so that quark mass matrices are diagonalized. The main RGE effects from  $M_{\text{GUT}}$  to  $M_W$  are those associated with the gluino mass and third generation Yukawa couplings. Regarding squark mass matrices, it is well known that diagonal elements receive important RGE contributions proportional to gluino mass that dilute the mass eigenstate nondegeneracy,  $m_{\tilde{D}_{A_i}}^2(M_W) \simeq c_A^i \cdot m_{\tilde{g}}^2 + m_{\tilde{D}_{A_i}}^2$  [3,13,14], with  $c_L^{1,2} \simeq (7, 7)$ ,  $c_L^3 \simeq (5.8, 5.0)$ ,  $c_R^{1,2} \simeq (6.6, 6.6)$ , and

$c_R^3 \simeq (6.6, 4.5)$  for  $(\tan\beta = 2, \tan\beta = 40)$ . In the limit of complete degeneracy of the initial diagonal values at  $M_{\text{GUT}}$  (equivalent to the constrained MSSM) off-diagonal elements after RGE running are necessarily proportional to masses and CKM elements and hence small. This means that any larger new contribution to off-diagonal elements, possibly due to a large quark-squark misalignment in the different  $K^A$  matrices, must be, at the same time, proportional to the difference of mass eigenstates at  $M_{\text{GUT}}$ . Then, in the SCKM basis the off-diagonal elements in the sfermion mass matrices will be given by  $(K^A \cdot M_{\tilde{A}}^2 \cdot K^{A\dagger})_{i \neq j}$  up to smaller RGE corrections. On the other hand, gaugino effects in the trilinear RGE are always proportional to the Yukawa matrices, not to the trilinear matrices themselves, and so they are always diagonal to extremely good approximation in the SCKM basis. Once more, the off-diagonal elements will be approximately given by  $(K^{A_L} \cdot Y_{u,d}^A \cdot K^{A_R q \dagger})_{i \neq j}$ .

After RGE running, flavor-changing effects in the SCKM basis can be estimated by the insertion of flavor-off-diagonal components of the mass-squared matrices normalized by an average squark mass, the so-called mass insertions (MI) [1,9]. In the first place, we will analyze the  $LR$  MI. Because of the trilinear term structure, the  $LR$  sfermion matrices are always suppressed by  $m_q/m_{\tilde{q}}$ , with  $m_q$  a quark mass and  $m_{\tilde{q}}$  the average squark mass. In any case, this suppression is compulsory to avoid charge and color breaking and directions unbounded from below [15]. In particular, it is required that  $(\delta_{LR}^d)_{i \neq j} \lesssim \sqrt{3} \max\{m_i, m_j\}/m_{\tilde{q}}$ , which implies that  $(\delta_{LR}^d)_{12} \lesssim \sqrt{3} m_s/m_{\tilde{q}} \simeq 3.2 \times 10^{-4} (500 \text{ GeV})/m_{\tilde{q}}$  and  $(\delta_{LR}^d)_{13} \lesssim \sqrt{3} m_b/m_{\tilde{q}} \simeq 0.01 (500 \text{ GeV})/m_{\tilde{q}}$ , where we take all quark masses evaluated at  $M_Z$  [16]. The phenomenological MI bounds given in Table I are stronger only for  $\text{Im}(\delta_{LR}^d)_{12}$ . Hence, this means that there is still room to saturate  $\varepsilon'/\varepsilon$  with  $LR$  mass insertions. However, these bounds imply that, under general circumstances, it is not possible to saturate simultaneously  $\varepsilon_K$  and  $\varepsilon'/\varepsilon$  with a  $|(\delta_{LR}^d)_{12}| = 3 \times 10^{-3}$  as suggested in Refs. [6,10].

For an explicit example of this we write the trilinear couplings in matrix notation as

TABLE I. Mass insertion bounds with  $x \simeq 1$  and  $m_{\tilde{q}} = 500 \text{ GeV}$ . They are completely symmetric under the exchange  $LL \leftrightarrow RR$  or  $LR \leftrightarrow RL$ .

$\Delta m_K$		$\varepsilon_K$	
$ \text{Re}(\delta_{LL}^d)_{12}^2 ^{1/2}$	$ \text{Re}(\delta_{LR}^d)_{12}^2 ^{1/2}$	$ \text{Im}(\delta_{LL}^d)_{12}^2 ^{1/2}$	$ \text{Im}(\delta_{LR}^d)_{12}^2 ^{1/2}$
0.040	0.0044	0.0032	0.00035
$\varepsilon'/\varepsilon$		$\Delta m_{B_d}$	
$\text{Im}(\delta_{LL}^d)_{12}$	$\text{Im}(\delta_{LR}^d)_{12}$	$ \text{Re}(\delta_{LL}^d)_{13}^2 ^{1/2}$	$ \text{Re}(\delta_{LR}^d)_{13}^2 ^{1/2}$
0.50	0.000021	0.098	0.033

$$Y_{d(u)}^A(M_{\text{GUT}}) = \begin{pmatrix} a_1^Q & 0 & 0 \\ 0 & a_2^Q & 0 \\ 0 & 0 & a_3^Q \end{pmatrix} \cdot Y_{d(u)} + Y_{d(u)} \cdot \begin{pmatrix} a_1^{D(U)} & 0 & 0 \\ 0 & a_2^{D(U)} & 0 \\ 0 & 0 & a_3^{D(U)} \end{pmatrix}, \quad (1)$$

where this form is found for instance in a type I string model [5,7]. As discussed above, gluino RGE effects are again diagonal in the SCKM basis and off-diagonal elements are basically given by the initial conditions. So, using unitarity of  $K^{D_L}$  and  $K^{D_R}$ , it is straightforward to get

$$(\delta_{LR}^d)_{i \neq j} = \frac{1}{m_{\tilde{q}}^2} [m_j(a_2^Q - a_1^Q)K_{i2}^{D_L}K_{j2}^{D_L*} + m_j(a_3^Q - a_1^Q)K_{i3}^{D_L}K_{j3}^{D_L*} + m_i(a_2^D - a_1^D)K_{i2}^{D_R}K_{j2}^{D_R*} + m_i(a_3^D - a_1^D)K_{i3}^{D_R}K_{j3}^{D_R*}]. \quad (2)$$

In the kaon system, we can make a simple estimate neglecting  $m_d$  and assuming  $K^{D_L} \approx K$ , which is the expected size if quark and squark masses have a common flavor origin [case (i) in the above introductory discussion]:

$$(\delta_{LR}^d)_{12} \simeq \frac{m_s}{m_{\tilde{q}}} \frac{(a_2^Q - a_1^Q)}{m_{\tilde{q}}} K_{12}K_{22}^* \simeq a4 \times 10^{-5} \left( \frac{500 \text{ GeV}}{m_{\tilde{q}}} \right), \quad (3)$$

where  $a$  is a constant typically between 0.1 and 1. Comparing with the bounds on the MI in Table I we can see that indeed this value could give a very sizable contribution to  $\varepsilon'/\varepsilon$  [6,7]. It is important to notice that the phase of  $(a_2^Q - a_1^Q)$  is actually unconstrained by electric dipole moment (EDM) experiments as emphasized in [7]. This result is very important: it means that even if the relative quark-squark flavor misalignment is absent, the presence of nonuniversal flavor-diagonal trilinear terms is enough to generate large FCNC effects in the kaon system.

Similarly, in the neutral  $B$  system,  $(\delta_{LR}^d)_{13}$  contributes to the  $B_d - \bar{B}_d$  mixing parameter,  $\Delta M_{B_d}$ . However, in the common flavor origin scenario [case (i)], i.e.,  $K^{D_L} \approx K$  (a direct extension of Ref. [6] mechanism), we obtain

$$(\delta_{LR}^d)_{13} \simeq \frac{m_b}{m_{\tilde{q}}} \frac{(a_3^Q - a_1^Q)}{m_{\tilde{q}}} K_{13}K_{33}^* \simeq a4.8 \times 10^{-5} \left( \frac{500 \text{ GeV}}{m_{\tilde{q}}} \right), \quad (4)$$

clearly too small to generate sizable  $\tilde{b}-\tilde{d}$  transitions, as can be seen comparing to the MI bounds in Table I.

Larger effects are still possible in our second scenario where flavor origin in the Yukawa sector and the soft-breaking sectors are unrelated [case (ii)]. In this framework, a large phase could be possible, and with a maximal value,  $|K_{13}^{D_L}K_{33}^{D_L*}| = 1/2$ , we would get  $(\delta_{LR}^d)_{13} \simeq a3 \times 10^{-3}$  (500 GeV/ $m_{\tilde{q}}$ ). Even in this limiting situation, this result is roughly 1 order of magnitude too small to saturate  $\Delta M_{B_d}$ , though it could still be observed through the  $CP$  asymmetries. Hence in the  $B$  system we arrive at a very different result: it is not at all enough to have nonuniversal trilinear terms, but, it is also required to have large flavor misalignment among quarks and squarks.

The situation for the  $LL$  and  $RR$  mass insertions is less defined due to the absence of any theoretical prejudice on

these mass matrices at  $M_{\text{GUT}}$ . In any case we can write these MI as

$$(\delta_A^d)_{i \neq j} = \frac{1}{m_{\tilde{q}}^2} [(m_{\tilde{D}_{A_2}}^2 - m_{\tilde{D}_{A_1}}^2)K_{i2}^{D_A}K_{j2}^{D_A*} + (m_{\tilde{D}_{A_3}}^2 - m_{\tilde{D}_{A_1}}^2)K_{i3}^{D_A}K_{j3}^{D_A*}]. \quad (5)$$

However, due to the gluino dominance in the squark eigenstates at  $M_W$  we can say that  $m_{\tilde{q}}^2(M_W) \approx 7m_{\tilde{g}}^2(M_{\text{GUT}})$ . Hence,  $(m_{\tilde{D}_{A_2}}^2 - m_{\tilde{D}_{A_1}}^2)/m_{\tilde{q}}^2 \approx 0.1bm_{\tilde{q}}^2$  with  $b$  a number  $\mathcal{O}(1)$ . Replacing these values in Eq. (5), this means, for the kaon system and assuming CKM-like mixing [case (i)],

$$(\delta_A^d)_{12} \simeq 0.1bK_{12} \simeq 0.02b. \quad (6)$$

Hence, in the presence of nonuniversality, sizable SUSY contributions to the kaon mass difference are expected. Regarding  $CP$  violation observables, with large phases in the  $K^{D_A}$  matrices, big contributions to  $\varepsilon_K$  arise (notice  $m_{\tilde{D}_{A_i}}^2$  are always real numbers). This is again equivalent to our result for the  $LR$  transitions: even if the sfermion mass matrices at  $M_{\text{GUT}}$  are flavor diagonal, large FCNC effects are produced in the  $K$  system with family nonuniversal masses.

In the  $B$  system, we must again distinguish our two possible scenarios. In case (i),  $K^{D_L} \approx K^{D_R} \approx K$ ,

$$(\delta_A^d)_{13} \simeq 0.1bK_{13} \simeq 8 \times 10^{-4}b, \quad (7)$$

clearly too small to be observed at the  $B$  factories. Nevertheless, in the presence of large mixing, still possible when flavor in the soft breaking terms has an independent source, we can get  $K_{13}^{D_A}K_{33}^{D_A*} \simeq 1/2$ . In this limiting situation  $(\delta_A^d)_{13} \lesssim 0.05$ , still reachable through  $CP$  asymmetries at the  $B$  factories in the presence of a sizable phase in  $K^{D_A}$ . So, we find again that to have observable effects in the  $B$  system it is required to have not only the presence of nonuniversality but also large quark-squark flavor misalignment.

In summary, in gluino mediated transitions large effects are expected in the Kaon system in the presence of nonuniversal squark masses even with a “natural” CKM-like mixing. However, in the  $B$  system, due to the much lower sensitivity to supersymmetric contributions, observable effects are expected only with approximately maximal  $\tilde{b}-\tilde{d}$  mixings.

Finally, we add a short comment on chargino contributions. The chargino sector is more involved due to the presence of the CKM mixing matrix and the additional mixing wino higgsino. However, for large and similar squark mixings in the up and down sector, chargino and gluino contributions are expected to be of the same order, barring special situations as light stop ( $M_{\tilde{t}} \lesssim 300$  GeV) and chargino. Indeed, in this case, the effects of the CKM matrix in chargino couplings are sufficiently small and can be neglected. Then, the flavor changing chargino and gluino vertices have similar mixing matrices and the difference in the couplings is compensated through the RGE relation  $\alpha_3/m_{\tilde{g}}^2 = \alpha_2/m_{\tilde{w}}^2$ . The only additional ingredient in chargino vertices is the presence of Higgsino. Higgsino couplings are suppressed by small Yukawa couplings with the exception of the top quark with  $Y_t \approx 1$ . Hence, the main difference between gluino and chargino contributions is the possible presence of a light stop due to the large top quark Yukawa coupling. The analysis of these new SUSY flavor contributions to  $B_d$ - $\bar{B}_d$  mixing in the presence of light stop and chargino was considered in Ref. [10] (for a discussion in the flavor universal case, see [17]). It was shown there that, for a light stop of 140 GeV and a chargino of 100 GeV and with a large  $\tilde{u}_L$ - $\tilde{t}_L$  mixing,  $K_{13}^{UL} \approx \lambda_c$ , it is still possible to produce contributions to  $\sin 2\beta$  as large as 0.78 with  $\delta_{\text{CKM}} = 0$ . However, this is a limiting case, light stop and chargino and, more important, a sizable mixing in the  $\tilde{u}_L$ - $\tilde{t}_L$  are required. Hence we conclude that chargino contributions are fit in our general scheme and only in a scenario with different flavor origin in the Yukawa and where soft-breaking sector sizable effects appear.

In conclusion, we have shown that in the kaon system large SUSY effects are naturally expected in any model with nonuniversal soft-breaking terms. In this direction, several works can be found in the literature [18,19] in the mass insertion context, and a complete analysis will be presented in a short time. On the other hand, a discovery of a supersymmetric contribution to hadronic  $B^0$   $CP$  asymmetries would signal the presence of a different origin of flavor in the breaking of SUSY.

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